Evaluation of a Submerged Remote Sensing SRS Technique

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LONG-TERM GOALS

To test and validate the Submerged Remote Sensing (SRS) technique[1,2] on a large Case I optical database that has been collected by the Center for Hydro-Optics and Remote Sensing, San Diego State University since 1990.

OBJECTIVES

The purpose of this work is to determine the optical properties of the atmosphere and water column using the SRS technique by knowing only the absolute downwelling irradiance at two wavelengths at a known depth, for a given date, time and position. It is straight forward to calculate the total path transmittance (a single value representing the combined water and atmospheric attenuation) by knowing the extra-terrestrial solar spectral irradiance, date, time, latitude and longitude. The difficulty is determining the two component parts of attenuation separately.

The SRS approach was to make measurements at two wavelengths and then use them in a set of equations, to solve for the separate attenuations. This required models describing the attenuation coefficients of sea water and the atmosphere and how they changed with wavelength for a variety of turbidities. Using the knowledge about the optical characteristics of the atmosphere[3,4] and seawater[5,6,7,8] it is possible to compute the transmission of light through the atmosphere, the air-water interface and through the water to a given depth under a set of environmental conditions. The pair of irradiances values is then used to perform the inverse computation to calculate the diffuse attenuation coefficient of the water ,$K(\lambda)$, and the optical depth of the atmosphere for the two wavelengths. It has been shown that there exists an apparent spectral relationship between $K(\lambda)$ and the various water types found in the open ocean[5,6,7,8]. The SRS was originally validated (Petzold and Austin, 1987) using a limited number of optical stations (54, n = 221) and fast scanning Multispectral Environmental Radiometers (MERs, Biospherical Instruments, Inc.). The purpose of this study is the evaluation of the SRS performance using a more extensive and diverse optical database.

APPROACH

The method presented here was to retrieve the characteristics of the atmosphere from optical measurements made at an arbitrary depth (z) in the open ocean. This technique can be organized in three phases: estimation of K at the reference wavelength, estimation of K at any other wavelengths (spectral K model) and estimation of the atmosphere characteristics (transmittance), using K and E_d at two wavelength.

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<u>K(490) Estimation</u> --- Algorithms were developed for deriving the diffuse attenuation coefficient (K) at 490 and 520 nm from the ratio of upwelling radiances $L_u(\lambda)$ at 443 and 550 nm[5]. This K_{Lu} relationship was formulated during the CZCS era, because (1) satellite ocean color sensor measured upwelling radiance (L_u), (2) the downwelling irradiance (E_d) is noisier and less reliable (enhanced backscatter by wave focusing and defocusing) than L_u measurements and (3) upwelling K_{Lu} tend to be less affected by the radiance distribution (i.e. solar zenith angle) and more associated with the water column inherent optical properties. For the SRS technique the relationship between K(490) and the radiance ratio was used:

$$K(490) = 0.0883 \left[\frac{L_u(443)}{L_u(550)} \right]^{-1.491} + 0.022 ,$$
(1)

where $L_u(\lambda)$ is the subsurface upwelling radiance and 0.022 (m^{-1}) is the attenuation coefficient for clear seawater at 490 nm. This model was developed from a number of sources and cruises covering a variety of water type (n = 88) and demonstrated that K(490), within the first optical depth (1/K), can be predicted from the radiance ratio (443/550) with an accuracy comparable to that of *in situ* measurements (Figure 1).
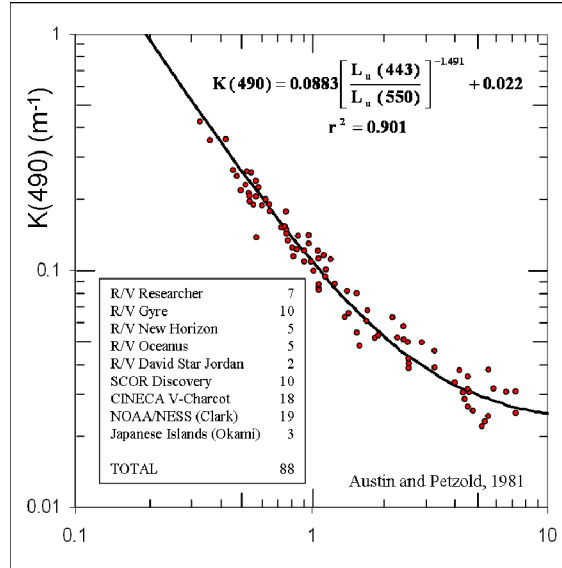
Figure 1: K(490) to radiance ratio [(L$_u$(443/L$_u$ (550)]algorithm.

<u>K(λ) Estimation</u> **---** A model was developed earlier[6,7,8] relating the spectral dependence of K(λ) to the value of K at a reference wavelength (λ_{ref}). The attenuation spectra were computed from downwelling spectral irradiance (Eq. 2) obtained from a variety of investigators working in widely separated ocean regions and using different measuring techniques and instrumentation.

$$K(\lambda) = -\frac{1}{z_2 - z_1} \ln\left(\frac{E_d(\lambda, z_2)}{E_d(\lambda, z_1)} \right)$$
(2).

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Values retrieved were examined and the value of K(490) was used as a classification index for the water type and varied from very clear water, 0.025 m^{-1}, to turbid water, 0.245 m^{-1}. Attenuation properties were calculated over the spectral region from 365 nm to 700 nm (68 wavelengths in total) at different depths (from 1 to 100 meters) and were plotted against the corresponding values of the classification index. These scatter diagrams provide a linear relationship that can be used to evaluate K as shown in Eq. 3:

$$K(\lambda_1) = M(\lambda_1)[K(\lambda_{ref}) - K_w(\lambda_{ref})] + K_w(\lambda_1), \tag{3}$$

where $M(\lambda)$ is the slope, λ_{ref} is the reference wavelength and K_w is the diffuse attenuation coefficient of pure sea water. Knowing $K_w(\lambda_{ref})$ and $K_w(\lambda_1)$, the slope $M(\lambda_1)$ [as tabulated in Table 4 on page 174 of reference (6)] and the classification index [$K(\lambda_{ref})$], the value of K at any wavelength can be estimated.

Estimation of the Atmospheric Properties --- This section will demonstrate how to estimate the atmospheric properties knowing K(490) and the downwelling irradiance (E$_d$) at two wavelengths, for fixed depth (Z). To understand this forward calculation there is a need to define some parameters:

▪ Atmospheric and surface transmittance;
▪ Diffuse transmittance through the water column;
▪ Irradiance at depth Z.

Knowing the time, date, location (latitude and longitude), sun zenith angle (θ_s) and extra-terrestrial solar spectral irradiance, $E_0(\lambda)$ the atmospheric transmittance ($T_{atm}(\lambda)$) can be evaluated using the following relationship[4]:

$$T_{atm}(\lambda) = \exp\left\{-\left[0.48\,\tau_{RAY}(\lambda) + \tau_{oz}(\lambda) + 0.5 \cdot (1-g)\,\tau_a(\lambda)\right]/\cos(\theta_S)\right\}, \tag{4}$$

where $\tau_{RAY}(\lambda)$, $\tau_{oz}(\lambda)$ and $\tau_a(\lambda)$ are the optical depths for one air mass due to Rayleigh scattering (air molecules), ozone absorption, and aerosols respectively. The asymmetry factor for aerosol particles is g and is approximately equal to 2/3. Using the assumption that the portion of the atmospheric attenuation caused by the aerosols is constant at all wavelengths, Eq. (4) becomes:

$$T_{atm}(\lambda) = \exp\left\{-\left[\tau_b(\lambda) + \tau_a(\lambda)\right]/\cos(\theta_S)\right\}. \tag{5}$$

The transmittance through the surface of the water, the surface transmittance T_S, is calculated using the Fresnel reflectance equations and the index of refraction of seawater:

$$T_S = 1 - \text{Fresnel Reflectance} \cong \frac{4n_1 n_2}{(n_1 + n_2)^2} \cong 0.98. \tag{6}$$

The diffuse transmittance through the water column (T$_w$), from the surface to the depth Z is:

$$T_W(\lambda) = \exp\left[-K(\lambda)z\right], \tag{7}$$

where $K(\lambda)$ is the mean diffuse attenuation coefficient of the water from the surface to depth, Z. The irradiance at depth Z is:

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$$E_Z(\lambda) = E_0(\lambda) \cdot T_S \cdot T_W(\lambda) \cdot T_{atm}(\lambda) \cdot \cos(\theta_s) \tag{8}$$

and the ratio of $E_Z(\lambda)$ at two wavelengths λ_1 and λ_2 is:

$$\frac{E_D(\lambda_2)}{E_D(\lambda_1)} = \frac{E_0(\lambda_2)}{E_0(\lambda_1)} \exp\{-[\tau_b(\lambda_2) - \tau_b(\lambda_1) + \tau_a(\lambda_2) - \tau_a(\lambda_1)]/\cos(\theta_s)\} \cdot \exp\{-[K(\lambda_2) - K(\lambda_1) \cdot z]\}. \tag{9}$$

The inversion of the above equation makes possible to evaluate the optical depths that can be used to solve equation (5) from which is also possible to evaluate the amount of irradiance that arrives at the surface of the ocean, by using the following relationship:

$$E_s(\lambda) = \cos(\theta_s) \cdot E_0(\lambda) \cdot T_{ATM}(\lambda). \tag{10}$$

WORK COMPLETED

<u>SRS Validation Assessment</u> --- The first goal was to check the implementation of the SRS using MATLAB algorithms to establish absolutely certainty that the SRS ran properly, generating correct estimates of integrated K_d. To verify implementation, a subset of the original 221 data sets was used in which all the input parameters were known (n = 12). After this validation, then the much larger U.S. Joint Global Ocean Flux Study (JGOFS) database from several different radiometers were used to measure above and in-water optical properties were analyzed. These vertical profiles of irradiance and above water surface irradiance were collected by C. Trees (CHORS) and used to determine the integrated diffuse attenuation coefficients at selected depths (20 m intervals). They were then compared to estimates of integrated K, using only irradiance at two wavelengths at the 20 m intervals with the SRS model.

<u>Visibility Laboratory Data</u> --- Petzold and Austin[1] developed the SRS technique using 54 stations from the following field campaigns:
- *R/V Captain Hook* (coastal waters off southern California, Mar-Apr 85)
- *USNS DeSteiguer* (N. Pacific-Bering Sea, Jun 85)
- *USNS Lynch* (GIN and Barents Seas, Aug 86)
- AUTEC (Tongue of the Ocean off Andros Island, Bahamas, Mar-Jul 86)

Three types of *in situ* radiometers were used:
- Multispectral Environmental Radiometer-MER (E_d, E_u and L_u at several wavelengths);
- Deck cell (E_s, 5 wavelengths);
- Illuminometer (above-water sensor that measures the irradiance at the surface; used when the deck cell was not available).

These instruments were deployed making optical measurements which allowed the direct determination of the mean diffuse attenuation coefficient of the water [$K(\lambda)$] and the atmospheric transmittance [$T_{atm}(\lambda)$]. To evaluate these parameters the 54 available stations were processed for six depths (20, 40, 60, 80, 100 and 120 meters); this resulted in a total of 221 set of samples.

North Atlantic Bloom Experiment Cruises, NABE --- U.S. participation in the North Atlantic Bloom Experiment consisted of three cruises to several study sites along 20° W and north of 40° N in the northeastern Atlantic. During the Spring of 1989, these process-oriented cruises monitored the annually occurring phytoplankton bloom to track the fluxes of the biogeochemical system. The estimation of K(490) was performed for one cruise (AT119-Leg5, May-Jun 89) where downwelling irradiance data were processed for eleven depths (20, 30, 40, 50, 60, 70, 80, 90, 100, 110 and 120 meters) at 30 stations (Table 1).

Equatorial Pacific Survey Cruises, EqPac --- The EqPac program was conducted in 1992 and four cruises took place; with a fifth benthic cruise and sediment trap legs adding to the overall study. These cruises consisted of two repeat meridional survey cruises (12°N - 12°S) at 140° W. The estimation of K(490) was performed for one of these cruises (TT007, Jan-Mar 92) and again this data were processed for eleven depths (20, 30, 40, 50, 60, 70, 80, 90, 100, 110 and 120 meters) at 15 stations (Table 1).

Arabian Sea Cruises --- The Arabian Sea process cruises focused on an area extending from the southeast coast of Oman toward India (15 °N 69 °E) and southward into the central northwestern Indian Ocean (10 °N 65 °E). Station locations were selected with the primary goal of investigating regions of seasonal upwelling associated with the Southwest Monsoon and determining the spatial extent of the influence of this upwelling. Research cruises were scheduled in July, August and September 1995 to coincide with the Southwest Monsoon; December, January and February to coincide with the Northeast Monsoon; and March-April to study the region during an intermonsoon period. Merged hydrographic data products have been compiled from three process cruises summarized in Table 1. The data used in this study are from the standard station locations for TTN-045, TTN-053, and TTN-054. To evaluate K(490) the downwelling irradiance was processed for eleven depths (20, 30, 40, 50, 60, 70, 80, 90, 100, 110 and 120 meters) at 80 stations (Table 1)

Cruise ID	Stations	Time	Location
AT119	30	25 Apr to 10 May 89	46°N 18°W - 60°N21°W
TT007	15	30 Jan to 13 Mar 92	12°N-12°S at 140°W
TTN-045	31	14 Mar to 8 Apr 95	22°N 57°E - 9°N 69°E
TTN-053	29	29 Oct to 25 Nov 95	25°N 56°E - 10°N 68°E
TTN-054	20	5 Dec to 24 Dec 95	20°N 58°E - 9°N 68°E
Total	**110**	--------------------------	-----------------------------

*Table 1: Cruises, number of stations, dates and geographic locations for SRS analyses.*

RESULTS

The first step performed was the duplication of the SRS methodology using the available references and the data points. After validation then the algorithms we were ready to be tested on other types of water using the available dataset from JGOFS.

Performance Evaluation with VisLab Subset --- The performance of the SRS model was tested against the VisLab data, but unfortunately all the input values used in the original development (221) were not available. Only 12 sets of data, found in a draft copy of the SIO Tech Memo 87-18, were used for this evaluation. We present the results of this comparison in Figures 2 and 3, showing the NURC estimate (+) and the value derived by Petzold and Austin (open square box). There are small differences at which time we do not know why, but in general the comparison is very good. As can be seen in the figures there were no trends between the two estimates as a function of measured K(490), depth or solar zenith angle.
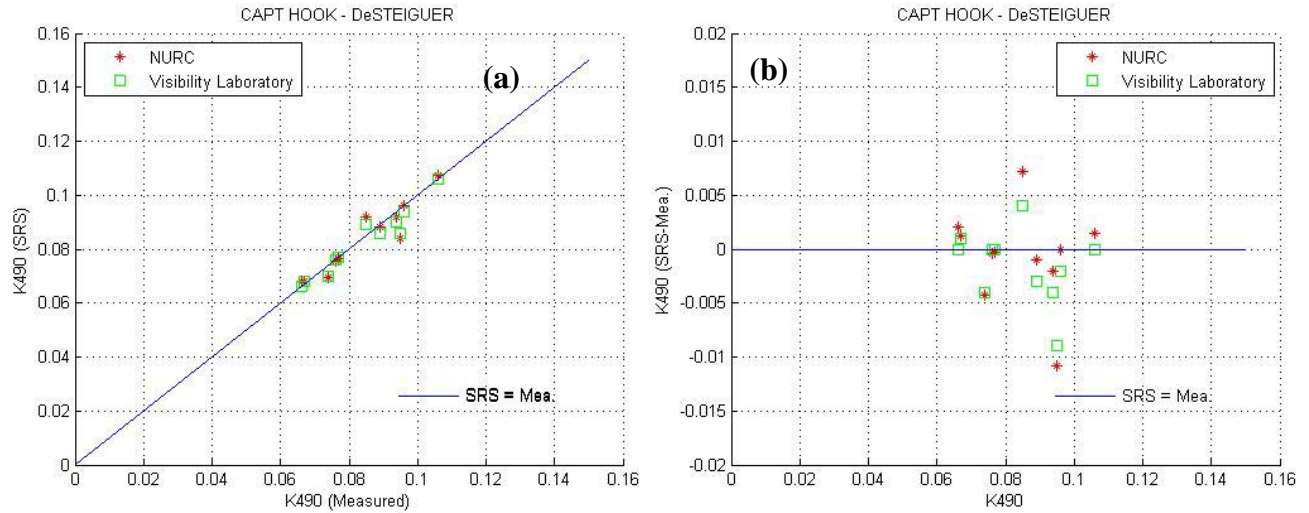
Figure 2: (a) K490 values from SRS computations (performed by Visibility Laboratory and NURC) versus K490 measured values. (b) K490 error (estimated – measured) versus K490.
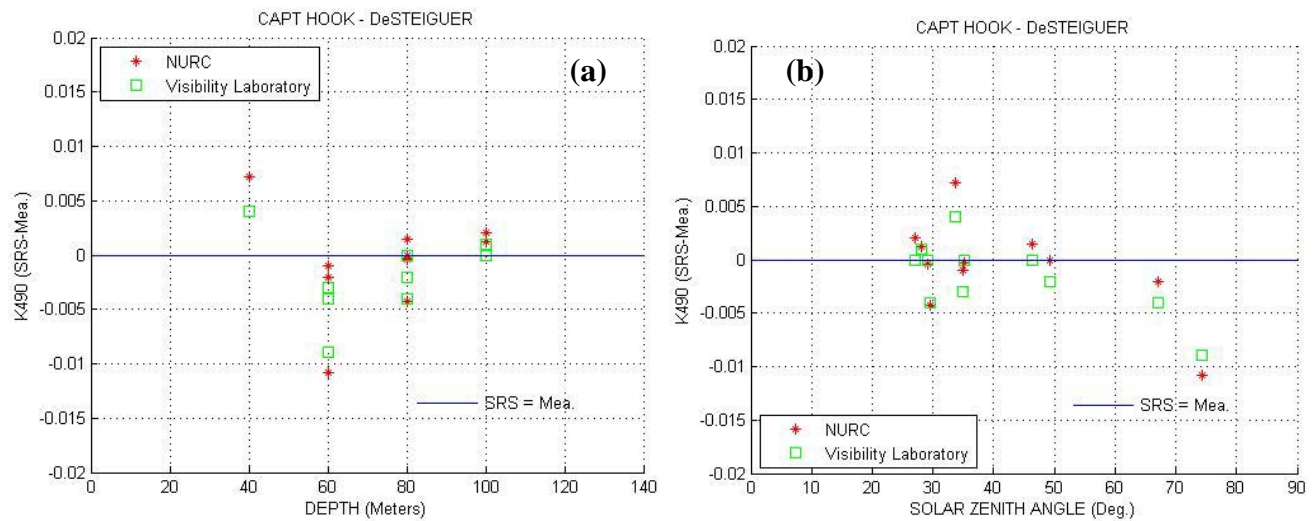
Figure 3: (a) K490 difference error from SRS computations (performed by Visibility Laboratory and NURC) versus depth [meters]. (b) K490 error (estimated – measured) versus solar zenith angle.

Table 2 shows a comparison of just one example (*R/V Captain Hook*, Station 14, 80 m depth) from the subset of VisLab data which includes additional ancillary data, such as cloud cover, depth, solar zenith angle and incident irradiance. The measured diffuse attenuation coefficients were not available in the draft report for the 410.6 and 439.9 nm wavelengths, although they did calculated K values from their SRS model. As such, we also extended our SRS estimates to include these wavelengths to provide a few more comparisons between the two SRS model implementations. Even under 100% overcast conditions as documented in Table 2, the SRS_{NURC} technique estimates integrated K(490) at 80 m to within $0.0022m^{-1}$.

SRS Implementation on JGOFS Data --- The following results show the estimation of K(490), using two known downwelling irradiances and one reference wavelength, for depth from 20 to 120 meters. As previously noted in reference [1], it's important to note that the accuracy of these estimation is

| SAMPLE #5					
Name	**Date**	**Atm.**	**Depth [m]**	**Zen [deg]**	**Measured Irradiance**
Capt Hook 14	4/4/1985	100% Overcast	80	29.6	E(486.5 nm) = 0.1292 E(547.9 nm) = 0.02377
λ [nm]	**Measured**	**SRS$_{VIS}$**	**SRS$_{Nurc}$**	**SRS$_{VIS}$ /Mea**	**SRS$_{NURC}$ /Mea**
Diffuse attenuation coefficient at MER wavelengths, K					
410.6	NaN	0.103	0.1029	NaN	NaN
439.9	NaN	0.090	0.0893	NaN	NaN
486.5	0.074	0.070	0.0718	0.944	0.9703
518.7	0.080	0.084	0.0853	1.051	1.0663
547.9	0.091	0.091	0.0915	0.997	1.0055

Table 2: This table shows an example of results for one of the 12 available data points (cruise name, date, depth, zenith angle, measured irradiance) and gives the results from the direct measurements (Measured) and from SRS computations performed by the Visibility Laboratory (SRS$_{VIS}$) and by NURC (SRS$_{Nurc}$).

related to the choice of the reference wavelengths and that this choice depends on the type of water. The following scatter-plots show the results for the data set described in section 3.2, 3.3 and 3.4. As showed in the following figures and quantified in Table 3, estimated K values are not as accurate as those retrieved with the VisLab data.
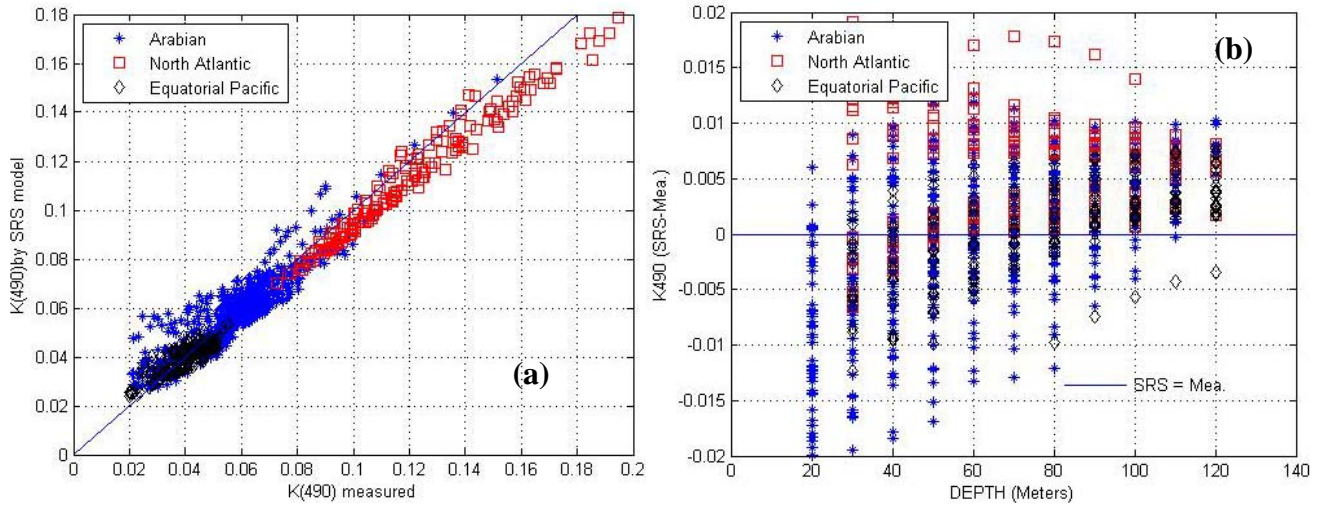
Figure 4: (a) K490 values from SRS computations versus K490 measured values for the Arabian (blue asterisks), Atlantis II – NABE (red squares) and EqPac (black diamond) data. (b) Error (K_estimated – K_measured) values versus depth [meters].
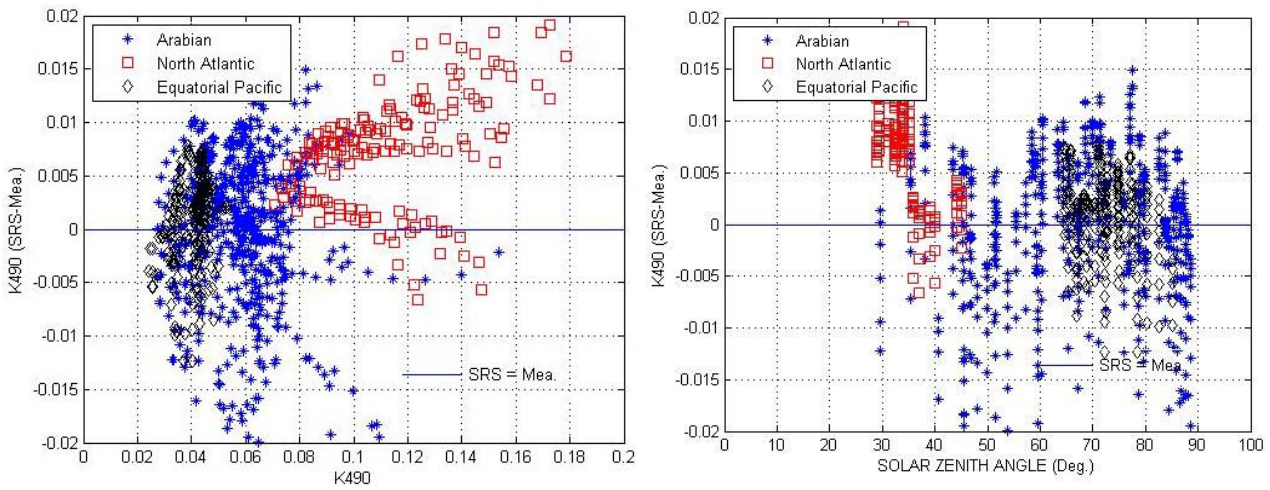
*Figure 5: K490 error (K_estimated – K_measured) versus K(490) and solar zenith angle (in a range that starts from 30 degrees to 90 degree).*

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Cruise	λ_1 and λ_1	$\sum$ points	$K_{SRS} - K_{Mea}$	K_{SRS}/K_{Mea}	$Rmse = \sqrt{\overline{\left\|K_{SRS} - K_{Mea}\right\|^2}}$
Cap.Hook - Desteiguer	439.9 nm 547.9 nm	12	Vm=-4.16e-4 Std=0.00428	Vm=0.9969 Std=0.04905	0.004125
Arabian Sea	442 nm 555 nm	781	Vm=-3.77e-4 Std=0.00709	Vm=0.9918 Std=0.1366	0.00710
NABE	440 nm 548 nm	300	Vm=0.007330 Std=0.00542	Vm=1.0638 Std=0.04071	0.009111
EqPac	440 nm 548 nm	520	Vm=-4.79e-4 Std=0.002895	Vm=1.02123 Std=0.107704	0.0029325

Table 3: This table lists the results for each available data set and compares the results of the direct measurements (K_{Mea}) with which retrieved using the SRS model (K_{SRS}).

This increase in model uncertainty can be attributed to the complexity of the water types (some coastal stations) found in the JGOFS databases, as well as the fact that the method used to calculate K is quite different between the VisLab and the JGOFS data.

The traditional method used by the VisLab was to estimate K (at z depth) as the local slope of the natural logarithm of the downwelling irradiance at z, measured within a depth interval spanning a few meters, and centered at depth z_m. It is assumed that K(z) is constant over the depth interval centered at z_m. The Visibility Laboratory used this classical derivative solutions for K, but also smoothed the diffuse attenuation profiles by manually drawing straight lines through plotted semi-log radiometric data and then determined the slope of these lines by estimating the axis intercepts (as represented by the three lines in Figure 6a).
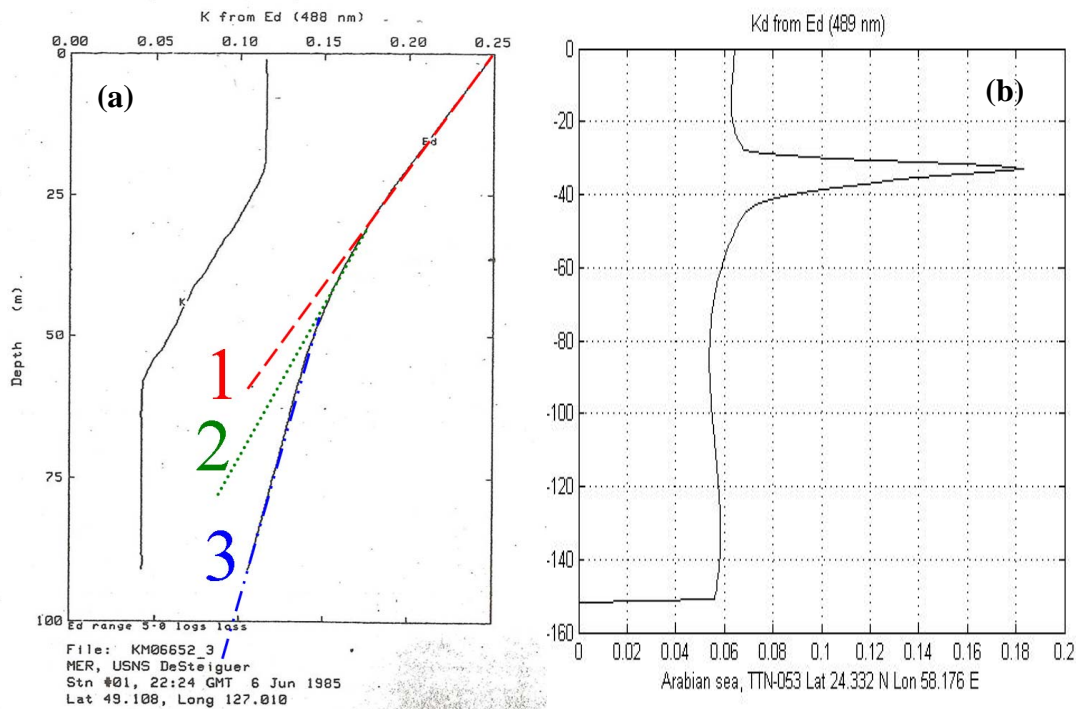
Figure 6: Comparison between K versus depth profile. (a) represents a typical profile from the Visibility Laboratory data, while (b) represents a profile from JOFS data.

The computer generated K profile (least squares regression fit) was then smoothed based on the slopes measured. This allowed for correction of the ship shadow, if present, and the increased noise near the surface caused by the enhanced backscattered generated by waves. The smoothed K profiles were then digitized using a drawing tablet. This computer technique to calculate K required a large depth interval of some ~20 m and hence caused the slopes in sharply defined layers, areas of high attenuation gradients, to be poorly represented.

For the data used in the JGOFS analyses to confirm the applicability of the SRS approach, an alternate method of determining K-profiles was used[9]. The K-profile is represented analytically by Hermititan cubic polynomials with unknown coefficients, consisting of a $K(z_n)$ and its derivative $dK(z_n)/dz$, at each of several discrete depths dividing the profile into finite depth elements.   The measured set of equations corresponding to each measured value $E(z)$ in the profile and depth z in the profile, are assembled into matrix form and the unknown set of coefficients $K(z_n)$ and $dK(z_n)/dz$ are determined using classical least-squares minimization. Compared to results of the derivative solution used at the Vis Lab, the integral method yields significantly more detailed representation of very sharp layers in bio-optical profiles (when compared to concurrent beam attenuation and chlorophyll fluorescence profiles). These sharp gradients in the JGOFS K profiles may introduce additional uncertainties when retrieving integrated K values.

IMPACT/APPLICATIONS

This report presents work performed to study, analyze, test and validate the SRS technique proposed by Petzold and Austin in 1987. The results are shown in the form of tables and plots with means and

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standard deviations. Comparison between NURC and VisLab showed very good agreement. The little differences found were probably due to different linear interpolation methodologies and approximations that have been performed to retrieve some coefficients (unfortunately, the original interpolation was not reported by the VisLab). We conclude that MATLAB algorithms developed at NURC work properly and that they are ready to be applied to different data sets. The results retrieved using new data sets (different types of water) are accurate (RMSE mean of the three data sets is 0.00637) comparable to what was retrieved in the past. The SRS technique provides a unique way to calculate water clarity from fixed depth observing platforms, such as AUV, moorings, submarines, US Navy SEAL delivery vehicles, etc. The SRS was validated in Case I waters and now needs to be evaluated and validated in Case II coastal waters.

RELATED PROJECTS

High quality IOP and AOP data will be collected during NATO Undersea Research Centre cruises (Ligurian Sea Calibration/Validation) in Oct 08 and Mar 09 in the Ligurian Sea and the Gulf of Lyons that could be used to evaluate and test the SRS technique in coastal Case II waters. In addition, Slocum gliders will also be deployed before and during the cruises to survey these areas. One of gliders has a 4 channel irradiance sensor, which will collect additional data for SRS evaluation.

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PUBLICATIONS

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